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by Tim J. Kreiter

Lewis Research Center

Cleveland, Ohio

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SUMMARY

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The payload capabilities of the Atlas-Centaur launch vehicle were evaluated for the 1969 Mars opportunity. In this evaluation, type I (heliocentric travel angle less than 180°) and type II (heliocentric travel angle greater than 180°) Earth-Mars trajectories were studied and both the direct and indirect launching modes were considered. The direct ascent launching mode is characterized by a continuous powered-flight phase, and launch windows are generated by varying injection true anomaly, launch azimuth, and injection velocity. For indirect ascent trajectories, two powered-flight phases exist with a parking-orbit phase separating the two burning periods. Launch windows are developed by varying launch azimuth and the time spent in the parking orbit.

Trajectories were selected that maximized launch-vehicle performance. Launch azimuth was restricted to less than or equal to 114°, and a minimum daily launch window of 60 minutes was imposed.

For type I trajectories and a 30-day launch interval, the indirect ascent Atlas-Centaur provides 1635 pounds of payload, whereas the direct ascent Atlas-Centaur provides only 1330 pounds. Launch azimuths between 49° and 64° are required for maximum payload for the indirect ascent mode, whereas an azimuth sector between 101° and 114° is sufficient for the direct ascent mode.

For type II trajectories and a 30-day launch interval, the indirect ascent Atlas-Centaur provides a payload of 1930 pounds, while the direct ascent vehicle provides about 1700 pounds. The type II indirect ascent trajectories utilize azimuths in the vicinity of 90°, but the type II direct ascent transfers require launch azimuths as low as 36° for maximum payload.

Author

INTRODUCTION

Current NASA interest in the exploration of the near planets, such as Mars and Venus, is evidenced by the recent start of the Voyager program. The major objective of this program is to orbit and to land substantial payloads at Mars during the 1971 and 1973 launch opportunities. As a possible forerunner to the Voyager and perhaps an extension of the Mariner program, which uses the Atlas-Agena vehicle, Mars mission payloads during the 1969 opportunity using the Atlas-Centaur launch vehicle are being studied.

According to present plans, the operational Atlas-Centaur vehicle will then be capable of flying in either the direct or the indirect ascent mode. The direct ascent mode requires no Centaur engine restart, and launch windows are developed by varying the injection true anomaly, launch azimuth and injection velocity of the outbound trajectory. The indirect ascent mode requires a second burning of the Centaur engines, and launch windows are developed by varying launch azimuth and the time spent in parking orbit prior to the second burn.

According to a previous study (ref. 1), in which Atlas-Centaur payload capabilities for the 1966-1967 Mars opportunity were investigated, the direct ascent launching mode provides greater payload potential than the indirect ascent launching mode for this opportunity.

Since the orbits of Earth and Mars are elliptical and inclined, rather than circular and coplanar, each launch opportunity will exhibit different energy and geometry requirements. Therefore, the 1969 Mars mission was investigated to determine the payload capabilities of both direct and indirect ascent Atlas-Centaur vehicles. Both type I and type II trajectories were considered. Type I trajectories, by definition, have heliocentric travel angles less than 180°, and type II trajectories have travel angles greater than 180°. Examples of these are presented in figure 1. In general, the type I trajectories are characterized by shorter flight times and result in shorter communication distances at encounter than the type II trajectories.

ANALYSIS

The patched conic, digital computer program discussed in reference 1 was used to compute the 1969 Mars trajectories presented herein. For a given launch date, the heliocentric trajectory is completely determined by specifying flight time. For convenience, launch azimuth was considered to be an independent variable in computing launch-window parameters.

Generally, for a given launch azimuth there are two possible times during the day when launch geometry requirements are satisfied. For direct ascent trajectories, the preferred solution is the one that maximizes payload. For indirect ascent trajectories, the preferred solution is the one with the shorter parking-orbit coast-time requirement, inasmuch as problems such as propellant settling and spacecraft orientation are reduced for shorter parking times. The payloads are essentially the same for both the long and the short coast-time solutions, if propellant boiloff and attitude control penalties are neglected.

In figure 2, burnout weight for a direct ascent Atlas-Centaur vehicle is shown as a function of injection true anomaly for geocentric vis viva injection energies of 8, 12, 16, 20, and 24 kilometers squared per second squared and a launch azimuth of 90°. Injection true anomaly is defined at the bottom of figure 2. Vis viva energy is twice the total energy of the geocentric conic. It can be seen from figure 2 that the preferred solution to the direct ascent, launch-geometry problem is the one for which the injection true anomaly is near 2.5°.

Direct ascent burnout weights may be computed throughout the launch window on the basis of vis viva energy (dictated by time of flight), launch azimuth, and injection true anomaly. Figure 3 presents the burnout-weight correction factor as a function of launch azimuth. The burnout weights taken from figure 2 were multiplied by this ratio to adjust for the appropriate launch azimuth.

In figure 4, burnout weight for an indirect ascent Atlas-Centaur is shown as a function of vis viva energy for a launch azimuth of 90° and a parking-orbit coast time of 20 minutes. Indirect ascent burnout weights may be computed with the aid of figure 4, figure 3 being used for launch azimuth corrections. The weight changes due to variable parking time within the prescribed 20-minute period were small and were therefore neglected.

Payload was computed by subtracting Centaur jettison weight from Atlas-Centaur burnout weight. The jettison weights used herein were 4102 pounds for the direct ascent vehicle and 4190 pounds for the indirect ascent vehicle. These jettison weights reflect Atlas-Centaur 15 performance capabilities as given in reference 2 and include 165 pounds of flight-performance reserves.

Figures 2 to 4 were generated by using the simplified booster program discussed in reference 1. The booster performance parameters used as input to this digital computer program were taken from reference 2.

Booster performance parameters (e.g., minimum burnout weight and Centaur jettison weight) change from month to month, inasmuch as the Centaur vehicle is in the middle of a research and development program. The data presented herein may be updated by referring to the most recent edition of reference 2. Changes in minimum burnout weight and jettison weight will move the payload curves vertically. The shapes of the curves are unaffected.

In this study, trajectories which yielded maximum payloads for the given launch date were selected. Only two constraints were imposed: (1) daily launch windows were to be equal to 60 minutes and (2) launch azimuths greater than 114° were not permissible.

RESULTS AND DISCUSSION

Direct Ascent Mode

For the direct ascent launching mode, payload is a strong function of vis viva energy and injection true anomaly, as evidenced in figure 2. Once flight time is specified, the energy and geometry requirements of the heliocentric trajectory are established for the particular launch date. A day-to-day flight-time search was therefore instituted to ascertain the best compromise between the energy and the geometry requirements (injection true anomaly) which resulted in maximum payload.

In reference 1, direct ascent trajectories for the 1966-1967 Mars opportunity were selected in a very special way. Flight times were chosen to make the declination of the outgoing geocentric asymptote equal to the negative of the launch site latitude. The resulting payloads were nearly maximum over the entire 1966-1967 launch period. The trajectories could not be selected in this fashion for the 1969 opportunity, however. Furthermore, no single criterion that would maximize payload capability could be employed over the entire launch period.

During certain portions of the launch period, payload potential could be maximized by launching at a fixed azimuth heading of 114°, which represents the maximum allowable launch azimuth.

In figure 5(a) is shown a typical day for which the constant launch azimuth technique provides the greatest payload potential. Launch azimuth and Atlas-Centaur payload are shown as functions of launch time for type I direct ascent trajectories to be launched February 14, 1969. Curve C provides the highest payload, but the launch azimuths are in excess of 114° during the launch window. If a family of trajectories that requires the limiting azimuth of 114° (curve D) is selected, payload will be maximum throughout the window. Time of flight is variable throughout the launch window along this curve.

On other days, the best payload capability is achieved by allowing both flight time and launch azimuth to vary across the launch window. In figure 5(b) such a day is shown. Launch azimuth and payload are shown as functions of launch time for type I direct ascent trajectories to be launched on May 15, 1969. The flight time of 281.25 is for the minimum-energy trajectory on this day. Note that minimum energy does not yield the greatest payload potential. The maximum payload curve on this day would be defined by an envelope curve that would, of course, encompass curves E, F, and G. For a 60-minute window, however, close to maximum payload capability may be obtained if a constant flight-time trajectory is chosen properly. Curve F in figure 5(b), depicting a 275-day trip, represents such a choice. On this day the launch window opens at about 20 hours and 43 minutes with an opening launch azimuth of about 108°. Window closing occurs at 21 hours and 43 minutes and the closing launch azimuth is about 99°. The payload potential is near 1570 pounds at window opening and at window closing.

In figure 6, the launch-azimuth envelope is shown as a function of launch date for type I and type II direct ascent trajectories. For the type II trajectories, flight times varied from day to day; however, they were considered constant on any given day. For the type I trips, constant launch-azimuth trajectories were used from January 30 to March 1 and from April 5 to May 10, 1969. Throughout the remainder of the interval, constant daily-flight-time trajectories were selected.

When the constant launch-azimuth technique was used, time of flight, geocentric vis viva injection energy, and communication distance at encounter varied on a given day. Their exact values depend on the instant that launch occurs within the 60-minute launch window. Launches made early in the window exhibit the shortest flight times and communication distances as well as the highest injection energies. The magnitude of this variation on a given day can best be seen from figure 7, which presents geocentric vis viva injection energy, communication distance at encounter, and time of flight as functions of launch date. The crosshatched areas represent the variations in these parameters over a 60-minute launch window on the days employing constant launch-azimuth trajectories.

In figure 8, Atlas-Centaur payload is shown as a function of launch date for type I and type II direct ascent trajectories. The payloads shown on this figure have been maximized either by assuming a family of trajectories all launched at 114° on a given day or by using the best constant flight-time trajectory on the given day.

Indirect Ascent Mode

For indirect ascent trajectories, payload is primarily a function of injection energy. Parking time does not have a strong effect on payload. In reference 1, the indirect ascent trajectories for the 1966-1967 Mars opportunity were selected to minimize the geocentric vis viva injection energy on a given day. Launch azimuths between 90° and 114° were used to develop launch windows for these trajectories.

For the 1969 opportunity, however, type I minimum energy trajectories exhibit peculiar geometry problems that preclude the use of launch azimuths near 90°, over most of the launch interval. This can be seen from figure 9, which shows the launch azimuth restrictions due to geometry as a function of launch date for minimum-energy type I trajectories. Azimuths near 90° do not become available until late in the interval, at which time parameters, such as flight time and communication distance at encounter, become rather large, as will be demonstrated later.

Launch azimuth is important not only from a performance point of view, where the 90° launches best utilize the Earth's rotational effects and thereby increase payload capability, but also from a range-safety and tracking standpoint. For these reasons nonminimum-energy trajectories were examined.

In figure 10, the results of this investigation are presented for a typical day in the interval. Launch azimuth and parking-orbit coast time are shown as functions of launch time for type I indirect ascent trajectories launched on February 14, 1969. Curve C is the minimum-energy trajectory for this day. Observe that the maximum launch azimuth that may be used is about 40° for the minimum-energy trajectory. If the trajectory selected arrives at Mars 10 days sooner (curve B), launch azimuths near 50° may be utilized. This requires a higher injection energy, but the performance gain, due to azimuth, offsets the injection-energy penalty and, in fact, results in a 32-pound payload increase. Further reductions in flight time are effective in bringing launch azimuths nearer to 90°, but the accompanying increases in injection energy become costly with respect to payload.

In figure 11, Atlas-Centaur payload is shown as a function of launch azimuth for 3 days in the 1969 launch interval. These days represent typical opening, middle, and closing days for a 30-day type I indirect ascent interval. The circles represent the payload capabilities for minimum-energy trajectories, and the curves show the tradeoff existing between payload and launch azimuth over the interval. In this study, the trajectories, which were selected to maximize payload, did, in fact, bring launch azimuth nearer to 90°. Payload compromises could have been made to further increase launch azimuth; however, such a compromise was not exploited since firm limits on launch azimuth have not been established.

Over most of the launch interval, the type I trajectories for maximum payload are somewhat more energetic than minimum-energy transfers. After about May 15, 1969, however, the trajectory geometry for minimum-energy transfers is such that azimuths about 90° are available and, hence, payload tradeoffs between azimuth and energy to maximize payload are ineffective. From that time on, minimum-energy trajectories are used. To illustrate this, in figure 12, launch azimuth and parking orbit coast time are shown as functions of launch time for the minimum-energy type I indirect ascent trajectory of May 15, 1969. The 60-minute window can be centered about the 90° launch azimuth point, thereby maximizing payload capability.

The launch geometry situation for the type II indirect ascent trajectories in 1969 is almost the reverse of the type I trajectories. The combination of minimum-energy trajectories and near-90° launch azimuths may be utilized over most of the launch interval. Azimuth requirements significantly different from 90° do not appear until about May 1, 1969. This can be seen from figure 13 in which the launch azimuth and parking orbit coast time envelopes are shown as functions of launch date.

Atlas-Centaur maximum payloads for type I and type II indirect ascent trajectories are shown as functions of launch date in figure 14, and the corresponding values of vis viva energy, communication distance at encounter, and time of flight as functions of launch date are shown in figure 15.

Comparison of Direct and Indirect Ascent Modes

From the data of figures 8 and 14, Atlas-Centaur payload capability is presented in figure 16 as a function of total number of launch opportunities for type I and type II direct and indirect ascent Mars trajectories in 1969. For the type I direct and indirect ascent trajectories there are two branches to the curve. The uppermost branch in each case reflects the additional launch opportunities afforded by a split-launch interval. This can better be visualized by referring to figure 14. With the assumption that a 1400-pound payload capability is required, a 60-day launch opportunity exists from February 7 to April 7, 1969. Later in the year (from May 8 to May 22), an additional 15 days are available. It should be noticed, however, that flight times and communication distances are relatively high for this second launch period, as evidenced in figure 15.

The results of this study are summarized in table I for a continuous 30-day launch interval.

Type II indirect ascent trajectories afford the greatest payload capability (about 1930 lb), and launch azimuths between 86.5° and 93.5° are satisfactory. Flight times as high as 300 days and communication distances up to 1.85 astronomical units, however, are required.

Type II direct ascent trajectories provide approximately a 1700-pound payload capability but require launch azimuths as low as 36°, and flight times and communication distances are greater than for the type II indirect ascent trajectories.

Type I indirect ascent trajectories provide about a 1635-pound payload capability and require launch azimuths between 49° and 64°. These trajectories exhibit flight times less than 175 days and communication distances less than 0.87 astronomical unit.

The payload capability for the type I direct ascent trajectories was 1330 pounds, and launch azimuths between 101° and 114° were required to generate launch windows. Flight times and communication distances were slightly greater than for the type I indirect ascent trajectories.

SUMMARY OF RESULTS

In the analysis of type I (heliocentric travel angle less than 180°) and type II (heliocentric travel angle greater than 180°) direct and indirect ascent trajectories to Mars, trajectories were selected to maximize launch vehicle performance (i.e., injected weight). A flyby type spacecraft was assumed and no special spacecraft constraints were considered. The results indicate that the indirect ascent mode outperforms the direct ascent mode in almost every category. For type I trajectories and a 30-day launch interval, the indirect ascent Atlas-Centaur provides a 1635-pound payload capability as compared with a 1330-pound capability for the direct ascent Atlas-Centaur. Furthermore, the flight times for the direct ascent trips are 21 to 45 days longer and the communication distances at encounter are greater by as much as 0.28 astronomical unit.

For type II trajectories and a 30-day launch interval the indirect ascent payload capability is about 1930 pounds. The direct ascent payload capability is approximately 1700 pounds. Direct ascent trips are 48 to 77 days longer and communication distance at encounter may be as high as 0.52 astronomical unit greater than the type II indirect ascent trajectory on the closing day of the launch interval.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 13, 1965.

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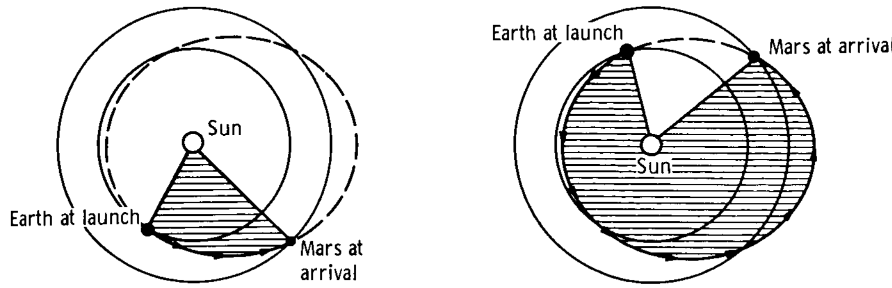
1. Kreiter, Tim J.: Comparison of Direct and Indirect Ascent Modes for the 1966-1967 Mars Opportunity with an Atlas-Centaur Launch Vehicle. NASA TN D-2739, 1965.

2. Hunt, A. E.: Centaur Monthly Configuration, Performance and Weight Status Report. GD/A 63-0495-20, General Dynamics/Astronautics, Jan. 21, 1965.

TABLE I. - RELATIVE PERFORMANCE OF TYPE I AND TYPE II DIRECT AND INDIRECT ASCENT TRAJECTORIES FOR THE 1969 MARS OPPORTUNITY

Trajectory type	Ascent mode	Launch interval[a]	Payload capability, lb	Range of trip time, days	Range of launch azimuth, deg	Range of communication distance, AU	Range of parking orbit coast time, min
I	Direct	Mar. 15 to Apr. 13	1330	125 to 196	101 to 114	0.60 to 1.15	--------
I	Indirect	Feb. 21 to Mar. 22	1635	170 to 175	49 to 64	0.68 to 0.87	10 to 15
II	Direct	Apr. 13 to May 12	1700	320 to 348	36 to 92	1.98 to 2.37	--------
II	Indirect	Mar. 16 to Apr. 14	1930	243 to 300	86.5 to 93.5	1.59 to 1.85	13 to 24

[a]30-day, continuous launch interval; daily launch window, 60 min.



(a) Type I transfer; central angle less than 180°.

(b) Type II transfer; central angle greater than 180°.

Figure 1. - Classification of interplanetary trajectories.

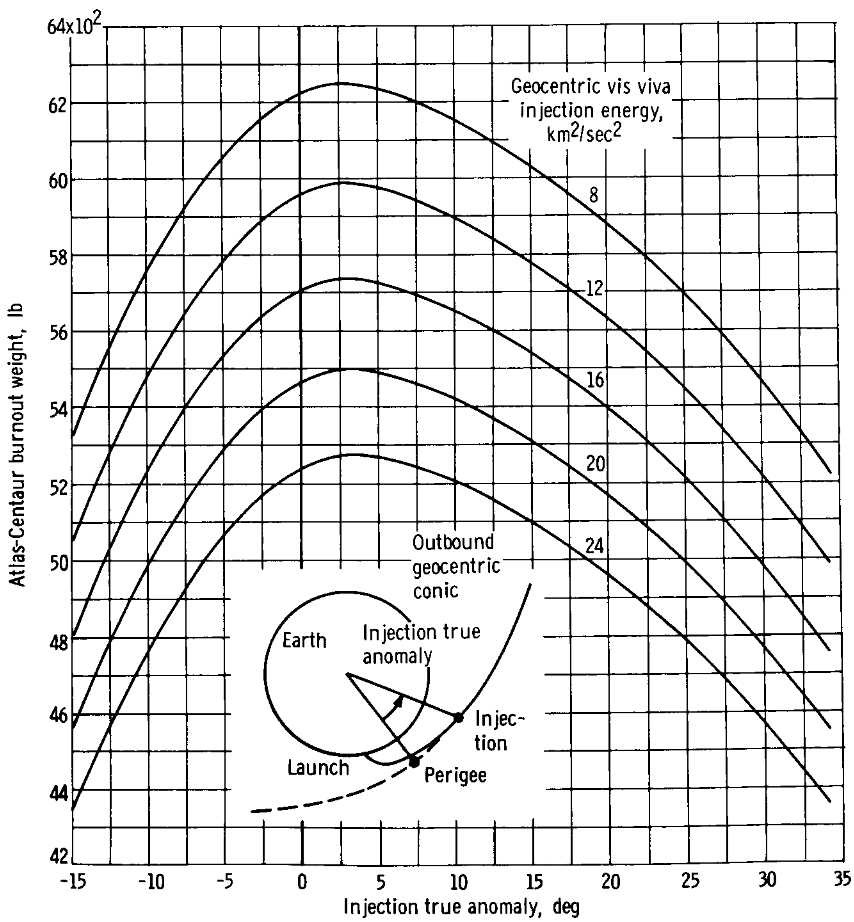


Figure 2. - Atlas-Centaur burnout weight as function of injection true anomaly. Launch azimuth, 90°; perigee altitude, 90 nautical miles.

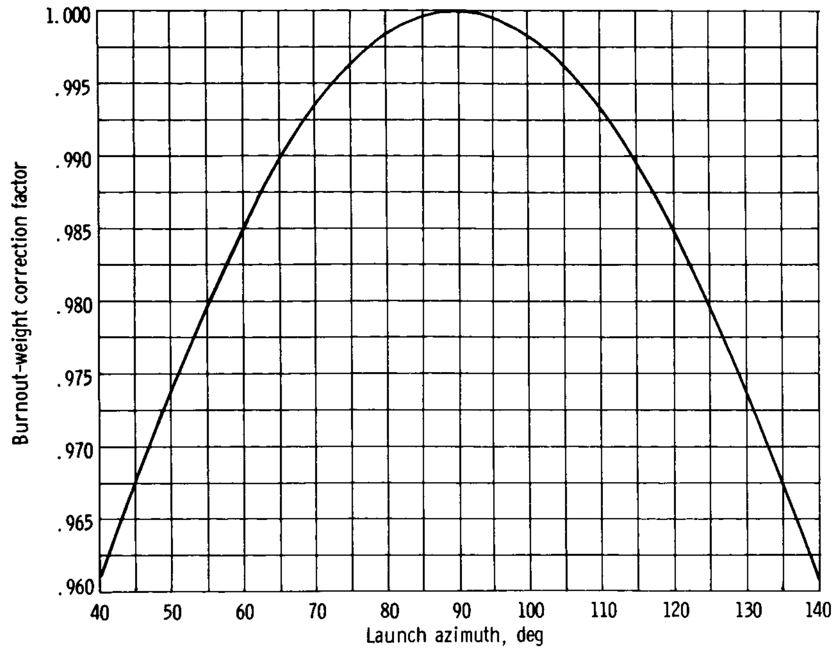


Figure 3. - Atlas-Centaur burnout-weight correction factor as function of launch azimuth. Geocentric vis viva injection energy, 12 kilometers squared per second squared; injection true anomaly, 5°.

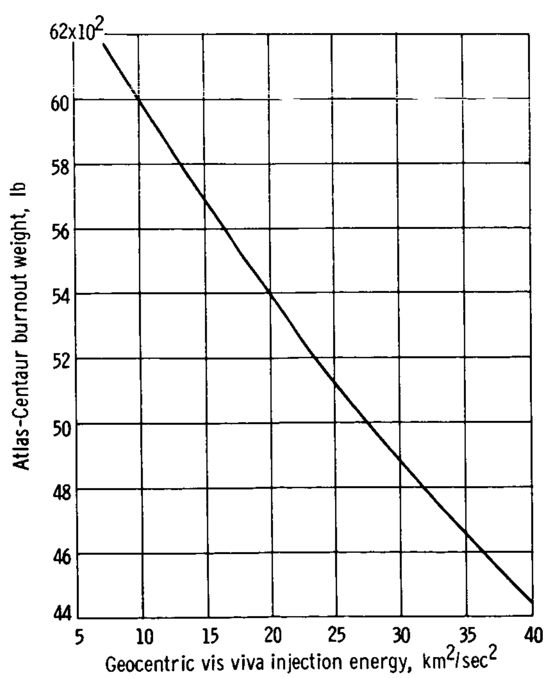
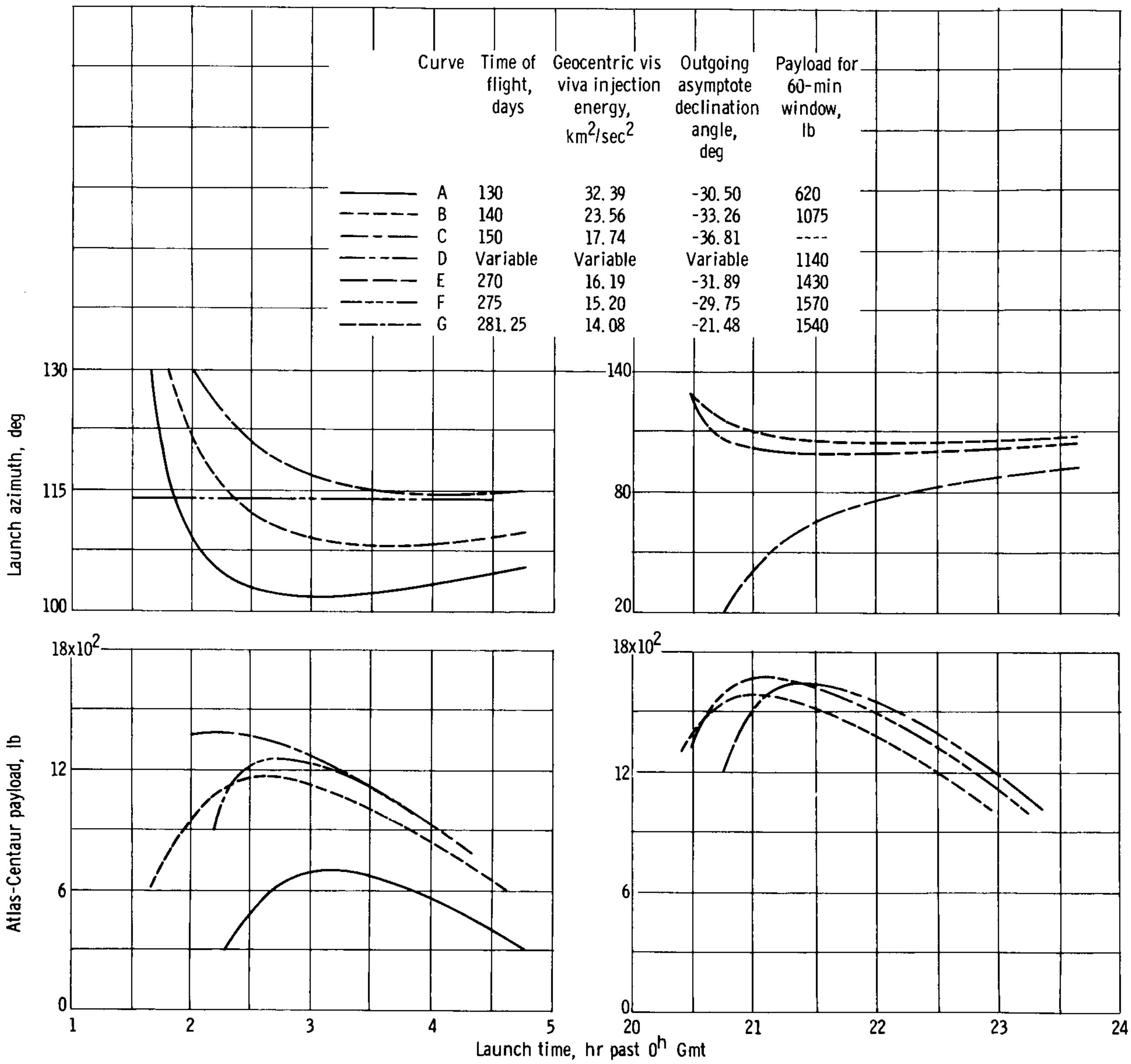


Figure 4. - Atlas-Centaur burnout weight as function of geocentric vis viva injection energy. Launch azimuth, 90°; parking orbit coast time, 20 minutes; parking orbit altitude, 90 nautical miles.



(a) Launch date, February 14, 1969.

(b) Launch date, May 15, 1969.

Figure 5. - Launch azimuth and Atlas-Centaur payload as functions of launch time for type I direct ascent trajectories.

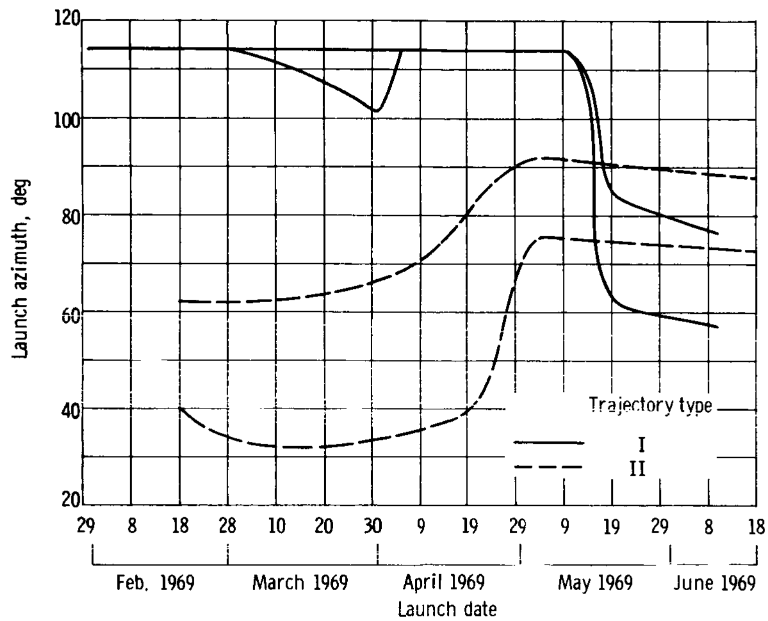


Figure 6. - Launch azimuth envelope as function of launch date for type I and type II direct ascent trajectories to Mars in 1969. Daily launch windows, 60 minutes.

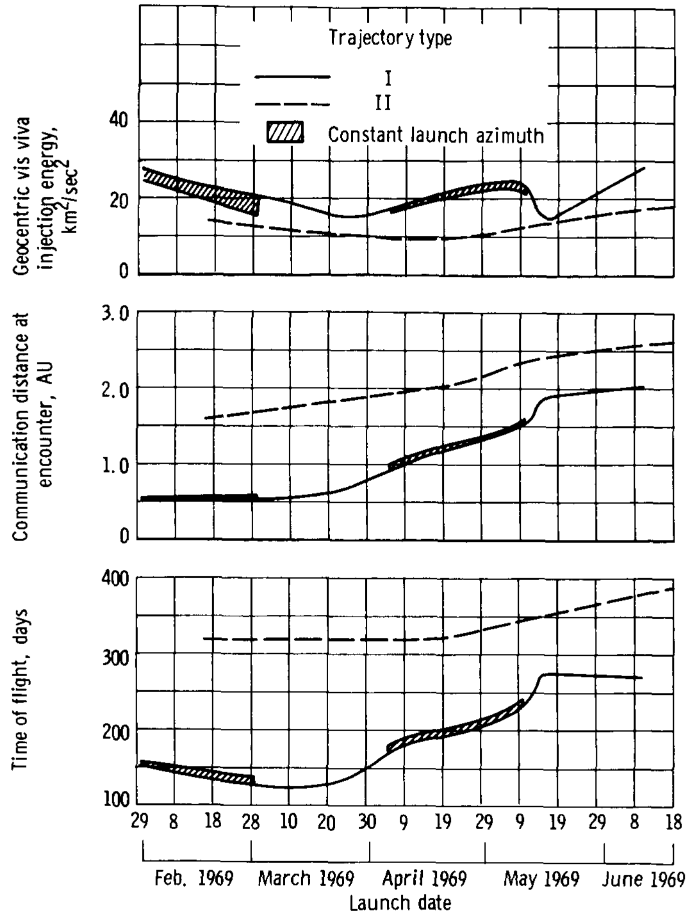


Figure 7. - Geocentric vis viva injection energy, communication distance at encounter, and time of flight as functions of launch date for type I and type II direct ascent trajectories to Mars in 1969.

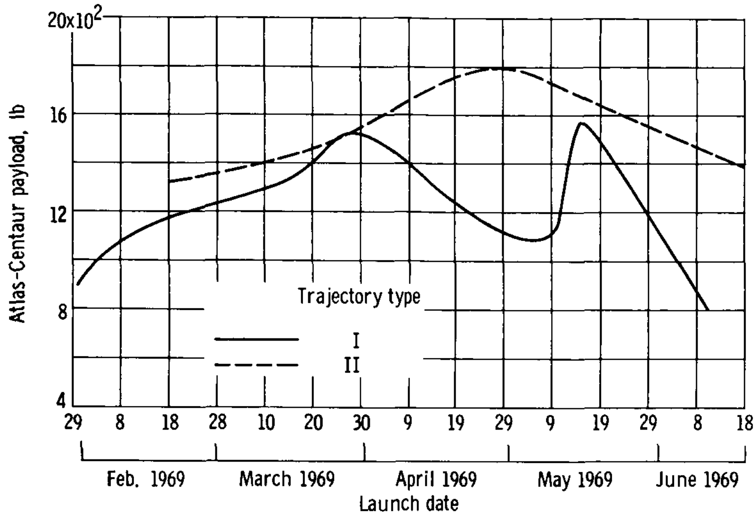


Figure 8. - Atlas-Centaur payload as function of launch date for type I and type II direct ascent trajectories to Mars in 1969. Daily launch windows, 60 minutes.

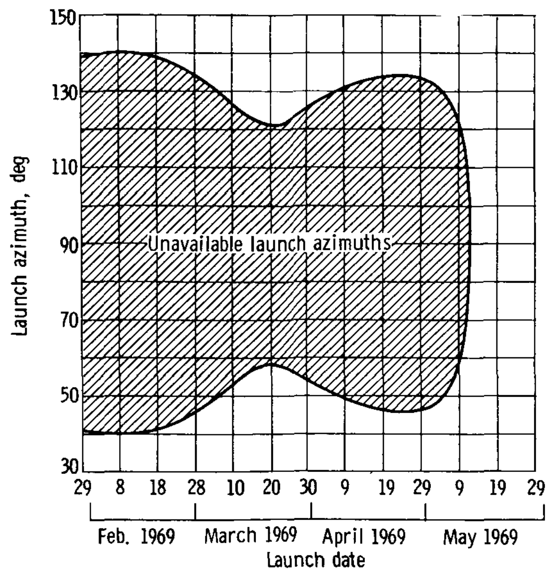


Figure 9. - Launch azimuth restrictions for type I minimum-energy trajectories to Mars in 1969.

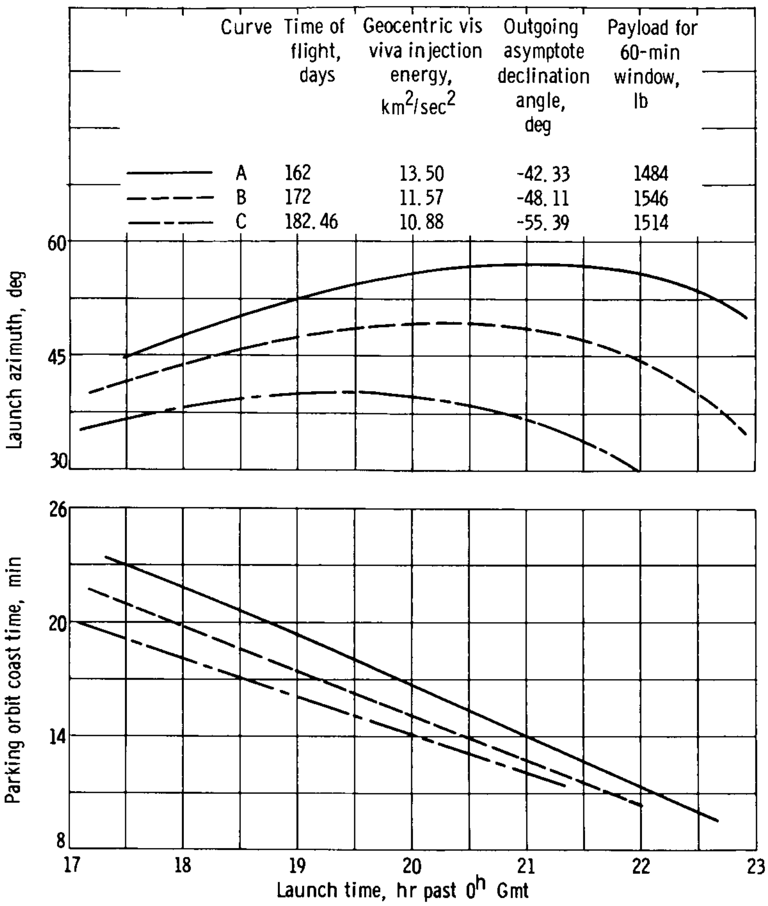


Figure 10. - Launch azimuth and parking-orbit coast time as functions of launch time for type I indirect ascent trajectories. Launch date, February 14, 1969.

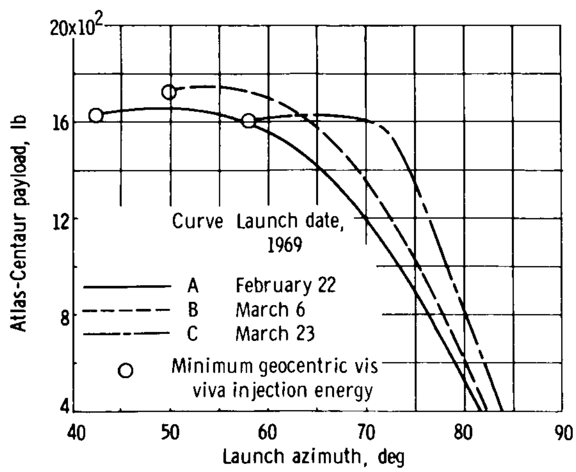


Figure 11. - Atlas-Centaur payload as function of maximum daily launch azimuth for type I indirect ascent trajectories.

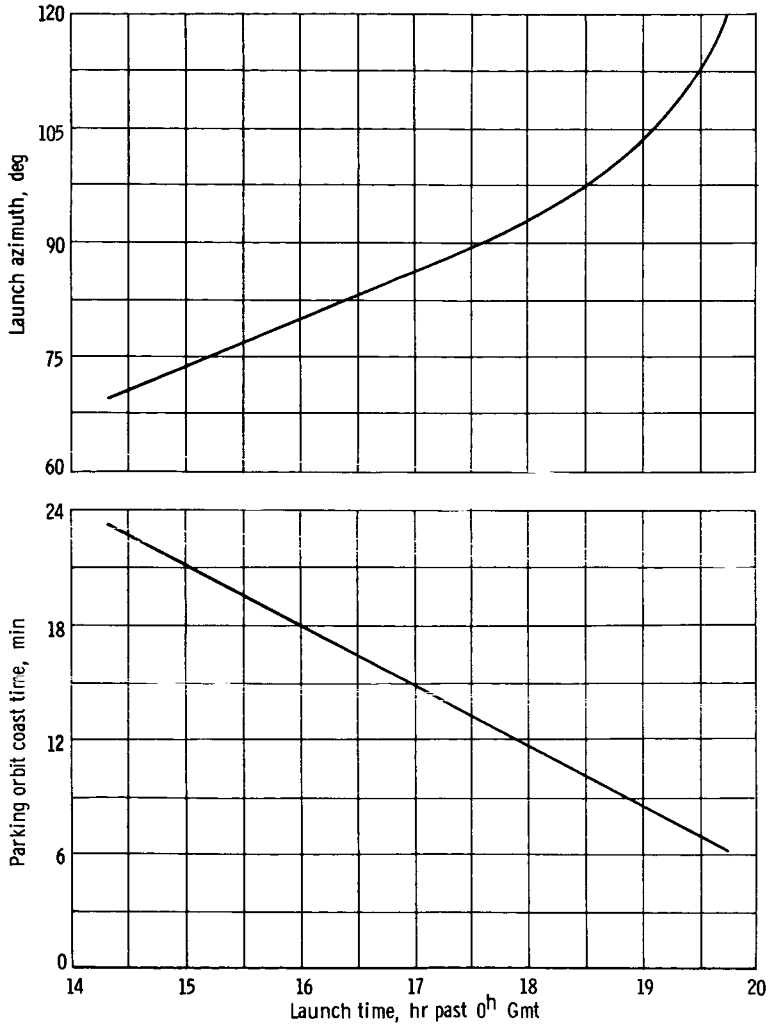


Figure 12. - Launch azimuth and parking-orbit coast time as functions of launch for type I minimum-energy indirect ascent trajectory. Launch date, May 15, 1969.

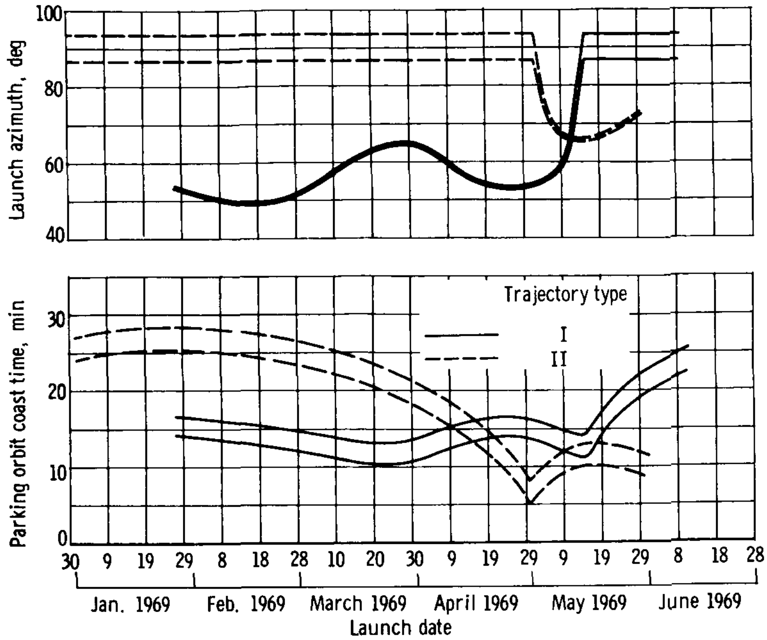


Figure 13. - Launch azimuth and parking-orbit coast time envelopes for type I and type II indirect ascent trajectories to Mars in 1969. Daily launch windows, 60 minutes.

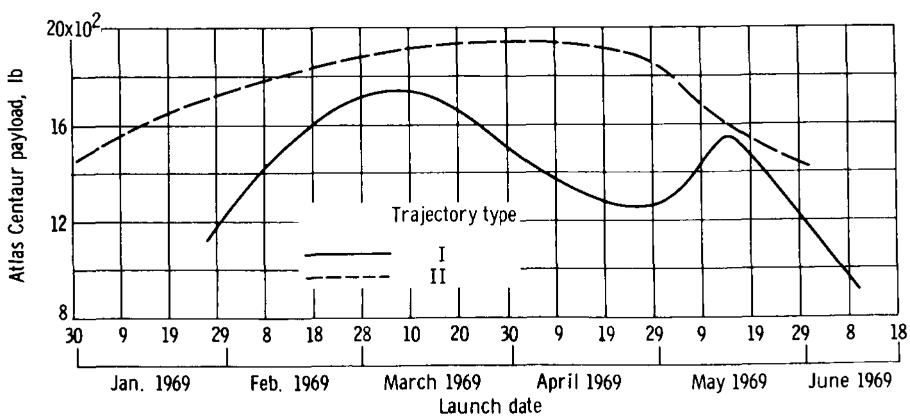


Figure 14. - Atlas-Centaur payload as function of launch date for type I and type II indirect ascent trajectories to Mars in 1969. Daily launch windows, 60 minutes.

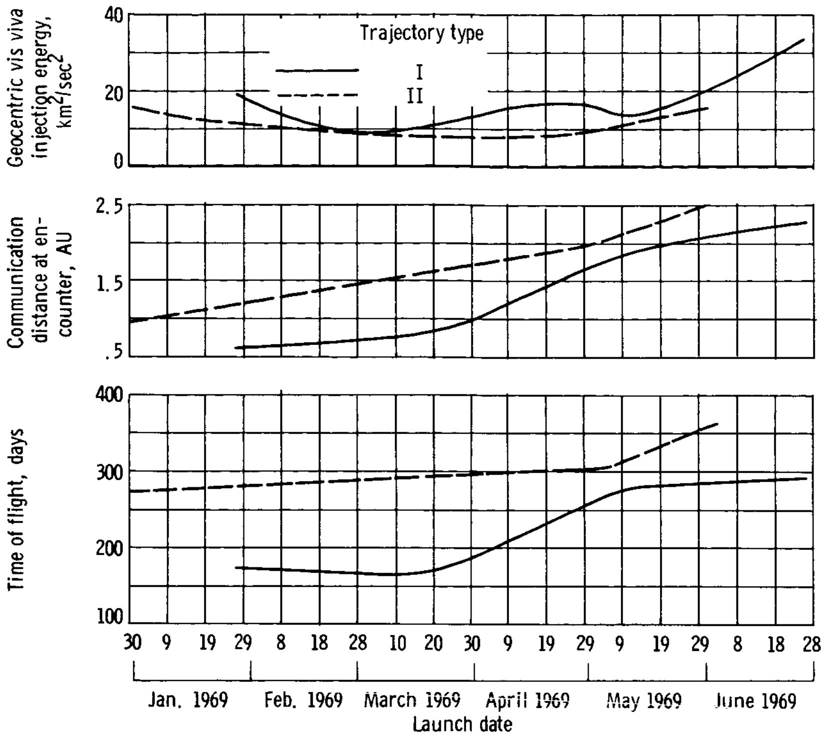


Figure 15. Geocentric vis viva injection energy, communication distance at encounter, and time of flight as functions of launch date for type I and type II indirect ascent trajectories to Mars in 1969.

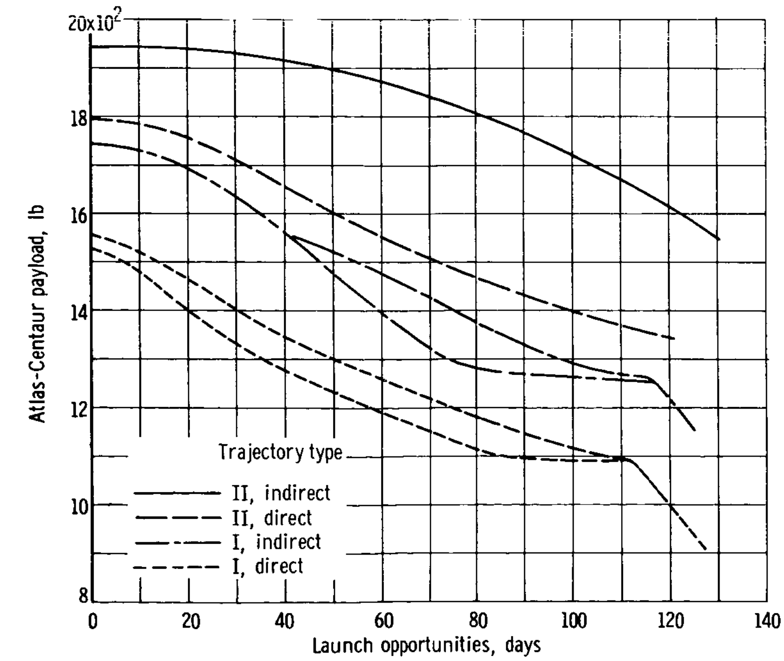


Figure 16. - Atlas-Centaur payload as function of total number of launch opportunities for Mars-1969 launch interval.